Petroleum and Geosystems Engineering

THE UNIVERSITY OF TEXAS AT AUSTIN

Signatures and Interpretations of Pump-in and Flow-back Tests in High Permeability and Low Permeability Formations

Yongcun Feng, K. E. Gray

The University of Texas at Austin

February 27, 2015

Outline

- A Review of Hydraulic Fracturing Tests
- Pump-in/Flow-back Test Signatures
- Effects of Permeability and Its Related Phenomenon on Pump-in/Flow-back Test Interpretation
- Pump-in/Flow-back Test Examples

Hydraulic Fracturing Tests

- Testing Wellbore/Cement Strength
- Determining Fracture Gradient (FG) and Minimum Horizontal Stress (Shmin)
  - Determining maximum drilling mud weight
  - Wellbore stability analysis
  - Hydraulic fracture stimulation design
- Understanding Mechanisms of Fracture Initiation and Propagation
  - Preventing wellbore breathing
  - Preventing and mitigating lost circulation

Hydraulic Fracturing Tests

- FIT (Formation Integrity Test)
  - Wellbore remains intact; cannot predict FG or Shmin
- LOT (Leak-off Test)
  - Fracture remains in the near wellbore region; affected by near-wellbore stress concentration
- Mini-Frac Test
  - Performed only in reservoir rock, commonly in cased and perforated intervals
- XLOT (Extended Leak-off Test) with Shut-in
  - Depends on rock properties (e.g. permeability, wettability), mud properties (e.g. mud type, viscosity, solids-content), and interaction between rock and mud (e.g. fluid leak-off, filter cake development)
- Pump-in/Flow-back (XLOT with Flow-back Phase)
  - Provides sufficient data for far-field stress estimation

Pump-in/Flow-back Procedures

A new well section is drilled below casing show (typically 10-20 feet)

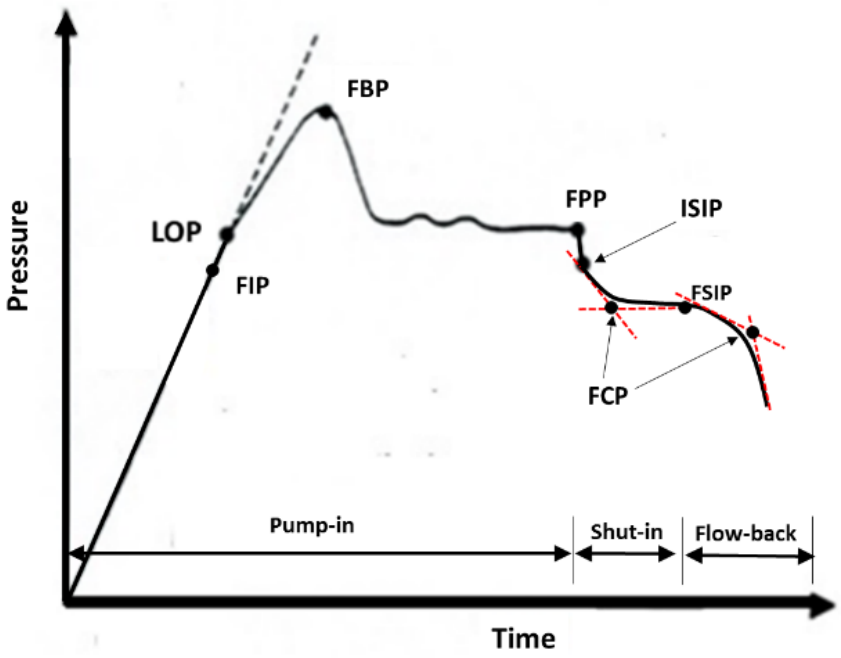
Wellhead is closed and fluid is slowly pumped into the well with a constant rate

Shut in the well for a while when a relatively constant FPP is reached

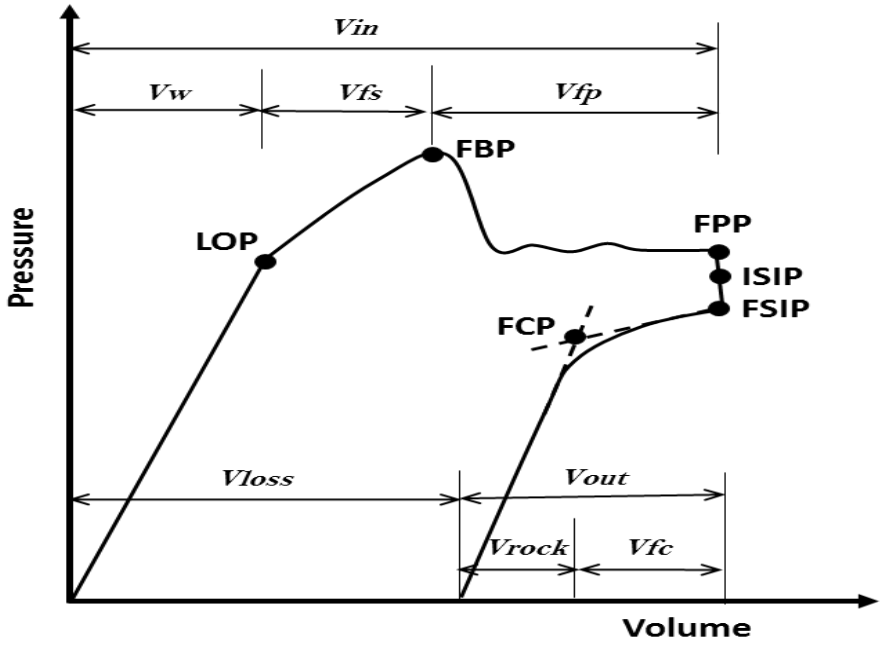
Open the well to allow fluid flow back to the surface with a constant rate or choke

Pump-in/Flow-back Signatures

- Pressure vs. time response



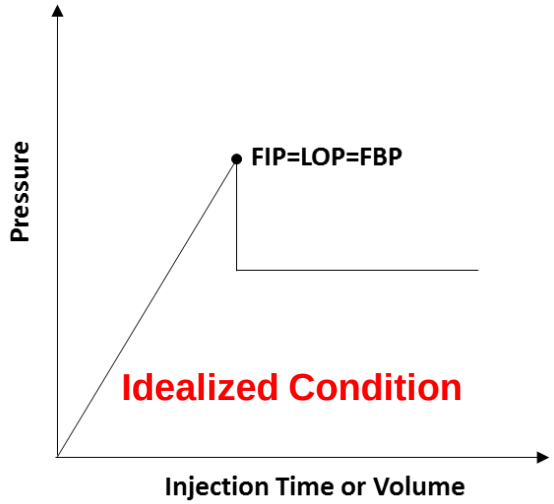
- Pressure vs. pump-in volume response

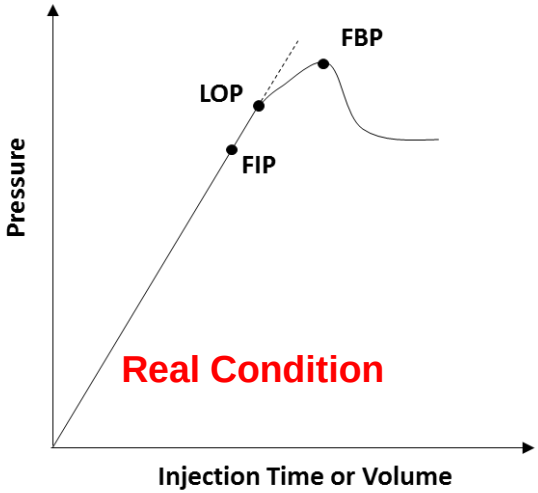


Modified after Fjær et al.

Permeability Related Effects on FIP, LOP and FBP

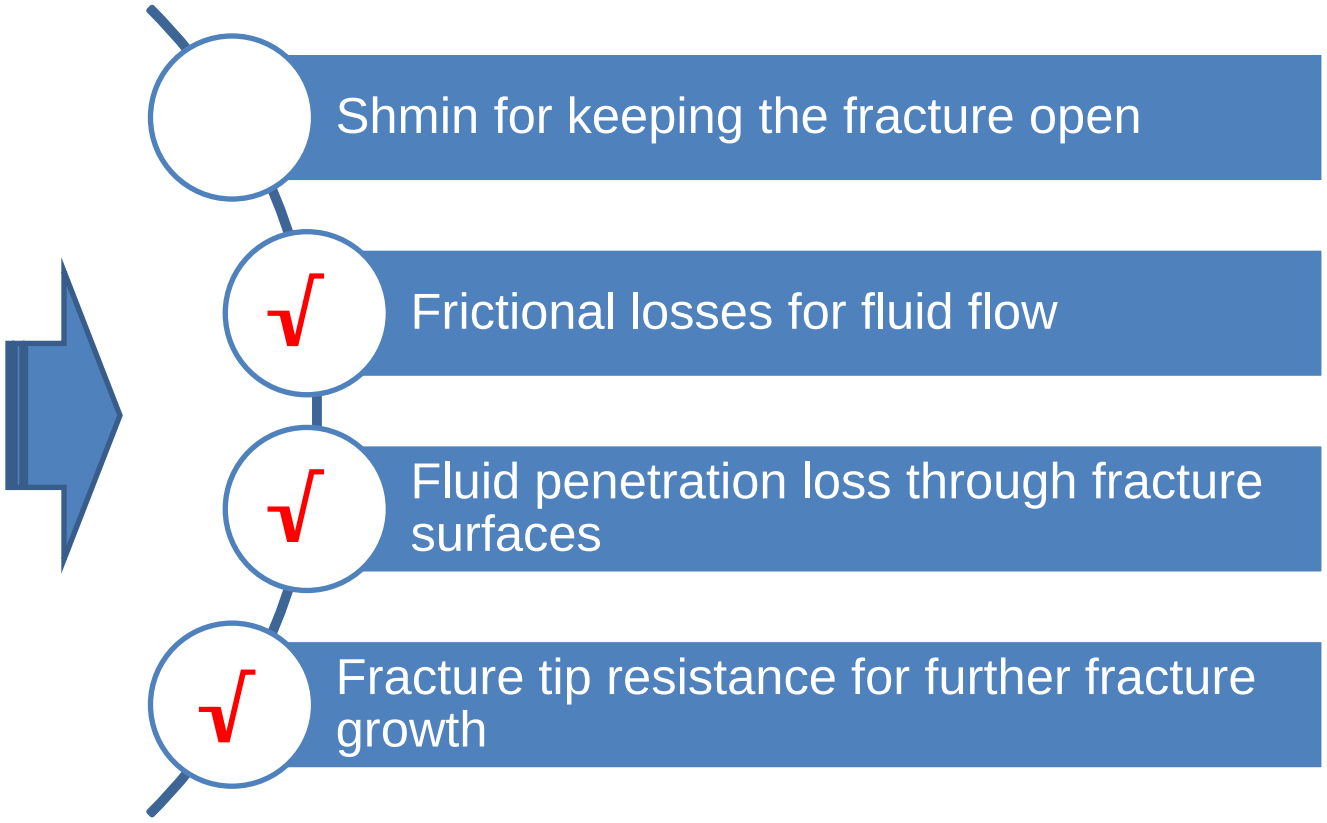
- FIP=LOP=FBP in idealized condition with impermeable rock, clean injection fluid, and low in-situ stress anisotropy
- Permeable wellbore usually has a relatively lower FIP due to wellbore fluid penetration
- LOP ≠ FIP with "dirty" mud in permeable rock
  - Filter cake forms with fluid leak-off
  - It can quickly seal micro-frac created at FIP, and arrest further fluid flow into the frac
  - Fracture can grow to a "significant" size without a detectable LOP
- FBP can also be increased by filter cake sealing, especially in high-perm formations





Permeability Related Effects on FPP

FPP is the total pressure required to overcome



Permeability Related Effects on FPP

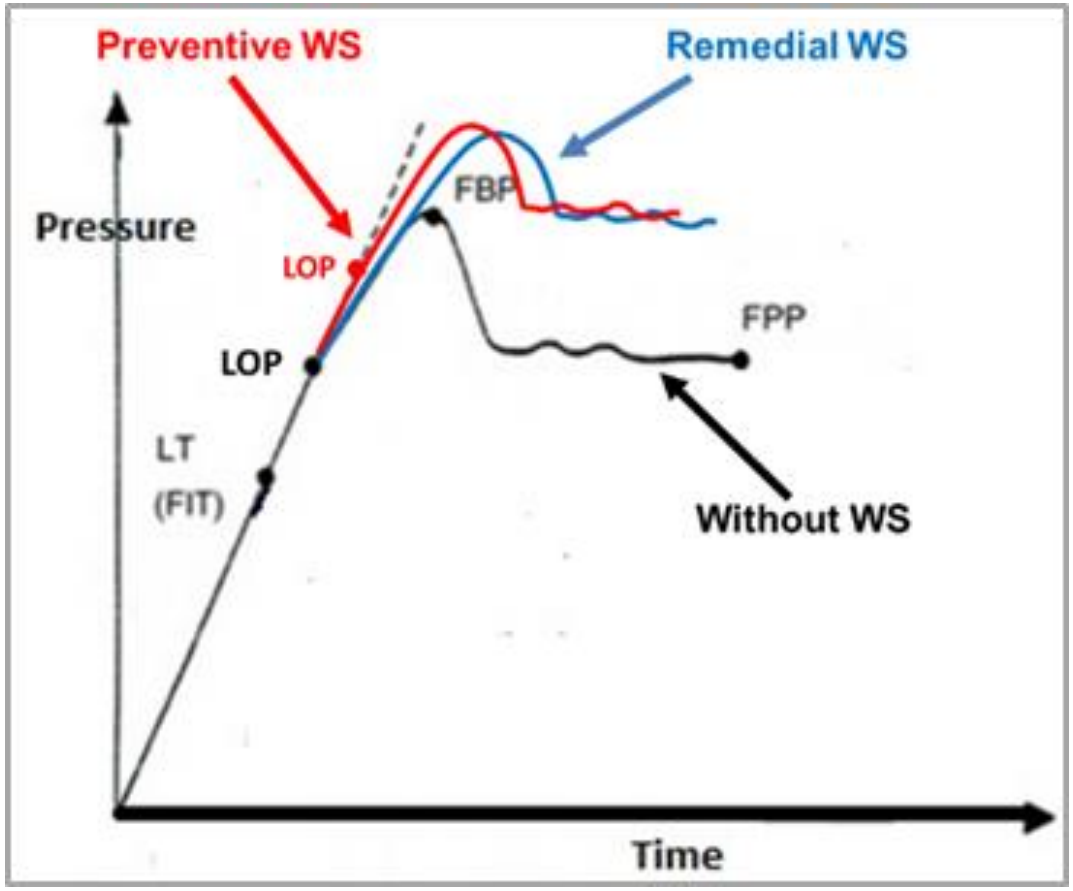
For rocks with relatively high prem

All contribute to increasing FPP

- Base fluid leak-off leads to a high solids density (fluid viscosity) in the fracture, resulting in an increased frictional loss
- Filter cake development on frac faces and around frac tip effectively isolates fracture from wellbore pressure
- Fluid loss reduces the energy in the facture acting on extending the fracture

Lost Circulation and Wellbore Strengthening

- Effects of permeability, fluid leak-off and filter cake development on LOP/FBP/FPP establish the fundamental theory for “Wellbore Strengthening” in petroleum drilling engineering



Perm. Related Effects on Estimation of FCP (Shmin)

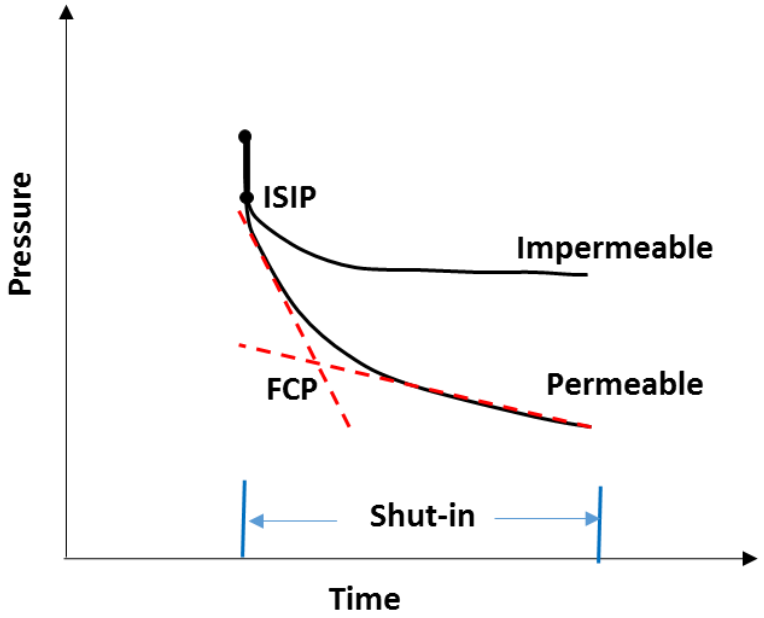
FCP (Shmin) from Shut-in

Permeable frac:

- fast leak-off → large pressure drop → frac closed → precise FCP

Impermeable frac (or permeable frac with tight filter cake):

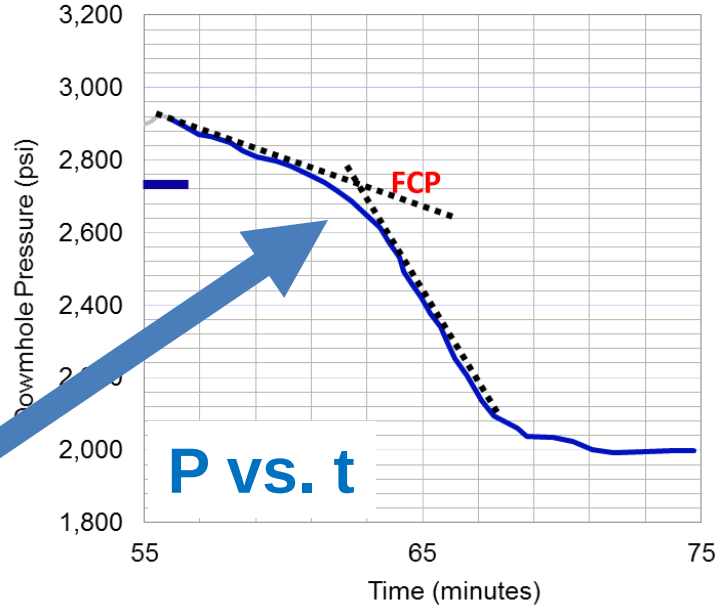
- limited leak-off → small pressure drop → frac open → inaccurate FCP

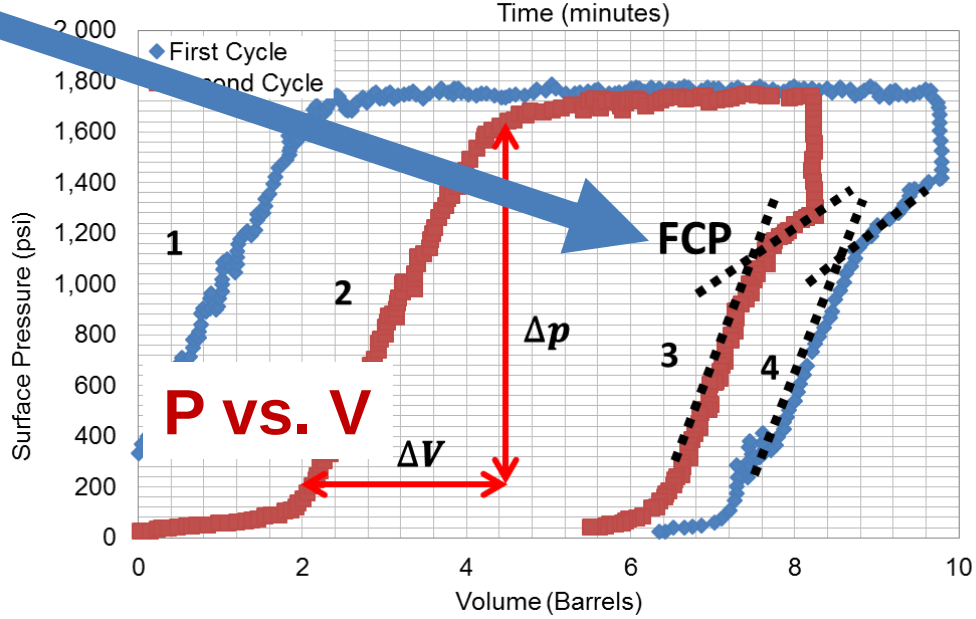


Estimation of FCP (Shmin)

FCP (Shmin) from Flow-back

- Fracture closure is always assured
- Especially suitable for formation with low perm and/or being tested with drilling mud
- Inflection points indicate system stiffness/compliance change due to fracture closure
- $C=\Delta V/\Delta p$, similar in phases 1, 2, 3 and 4 without frac or with closed frac
- FCP is the same in the 1st and 2nd cycles

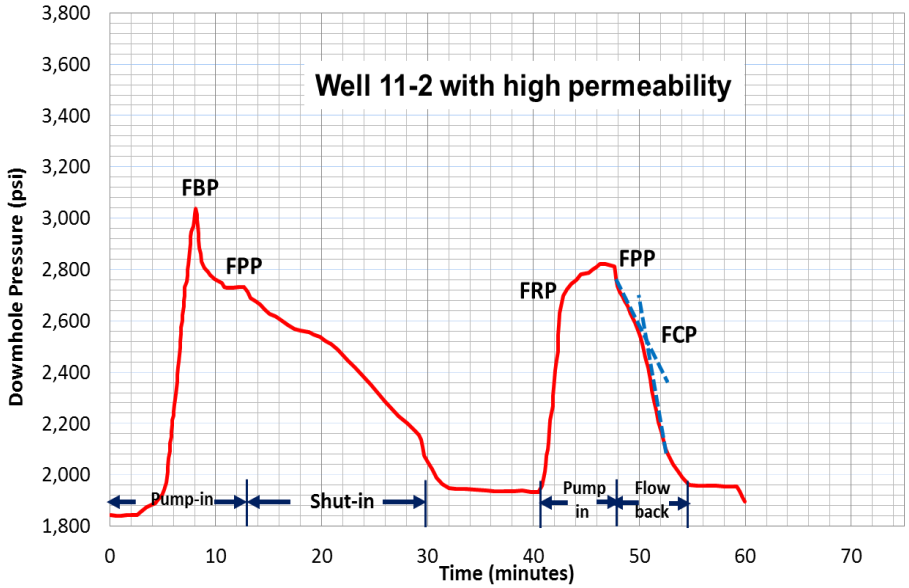




Data reproduced after Gederaas and Raaen

Pump-in/Flow-back Test Examples

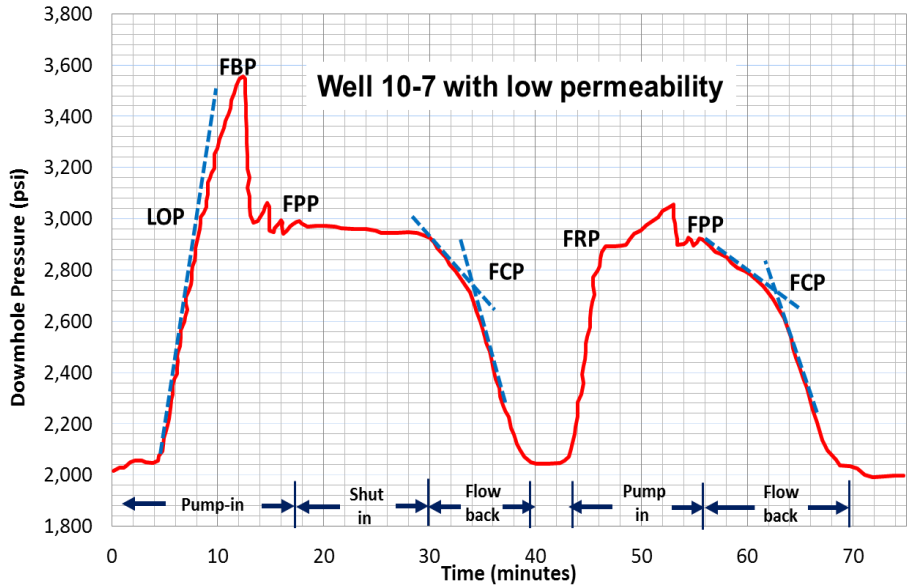
Tests in two neighboring wells in the North Sea (Okland et al. 2002)



Data reproduced after Okland et al

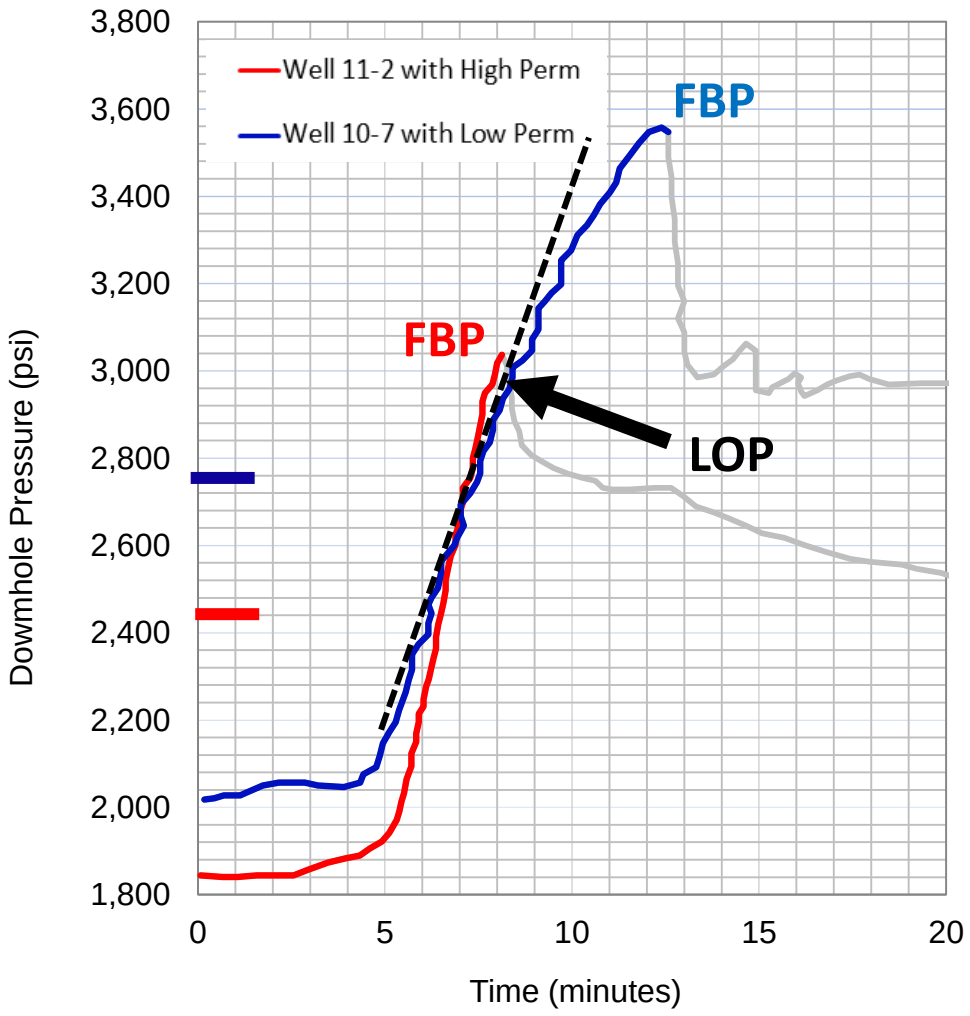
- Well 11-2:
  - Test @4097ft
  - Relatively High Perm.
  - S_{hmin}=2500psi

- Well 10-7:
  - Test @ 4284ft
  - Relatively Low Perm.
  - S_{hmin}=2740psi



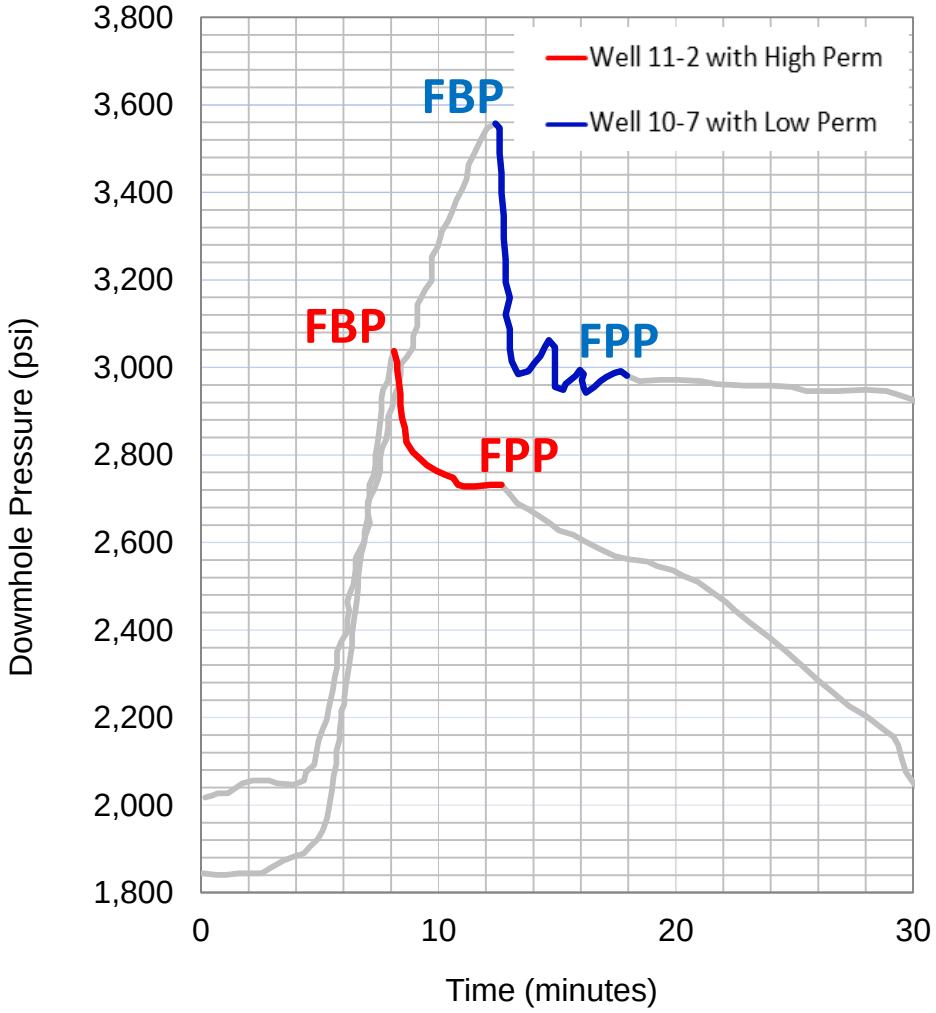
Data reproduced after Okland et al

Pressure Build-up



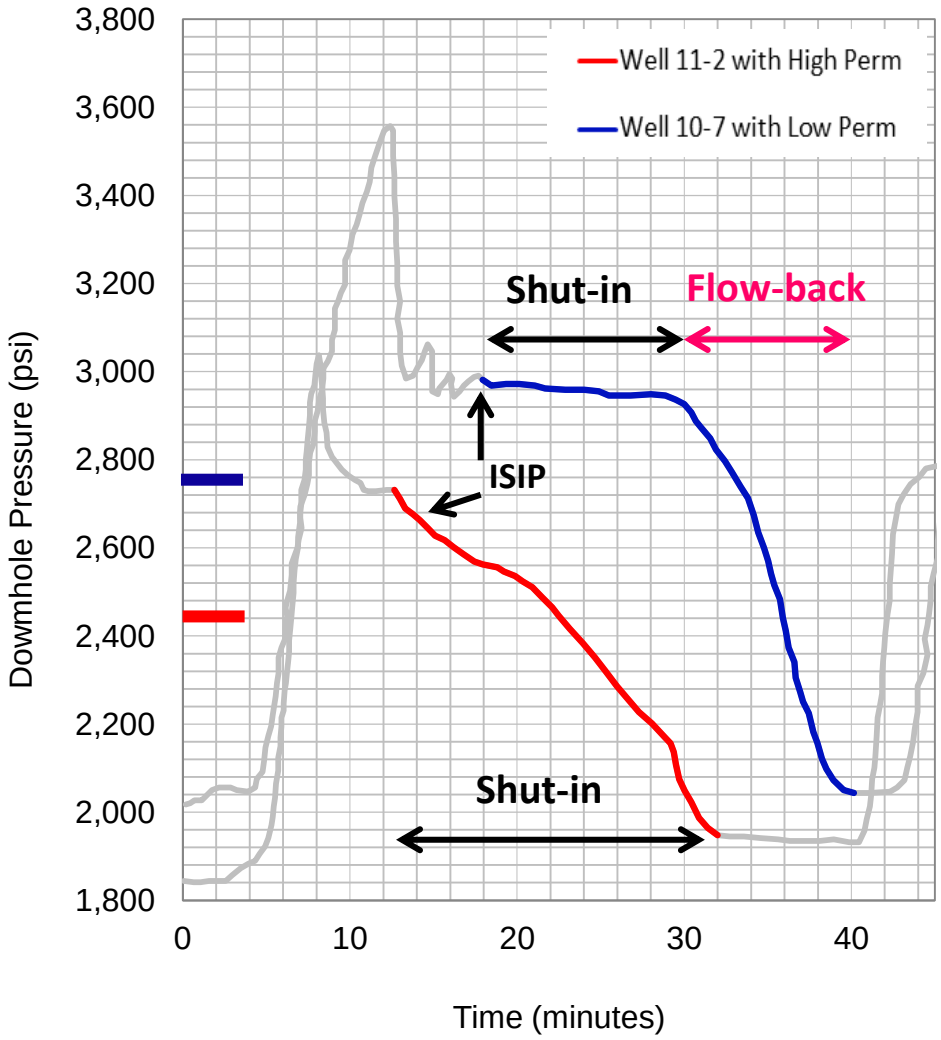
- Relatively clear LOP point in low-perm Well 10-7 compared with high-perm Well 11-2
  - Possibly due to filter cake sealing effect in high-perm Well 11-2
- Relatively lower FBP in high-perm Well 11-2
  - Lower depth
  - High-perm formation (usually with relatively smaller Passion's Ratio) transmits less overburden to horizontal stress
  - Fluid penetration

Fracture Propagation



- Sudden pressure drop after FBP in both cases
  - Fracture volume induced by propagation grows faster than injection rate
- Low-perm Well 10-7 experienced a larger pressure drop from FBP to FPP compared with high-perm Well 11-2
  - Low-perm rock: relatively high FBP, but low FPP (lack of filter cake development)
  - High-perm rock: low FBP, but relatively high FPP with a quality filter cake

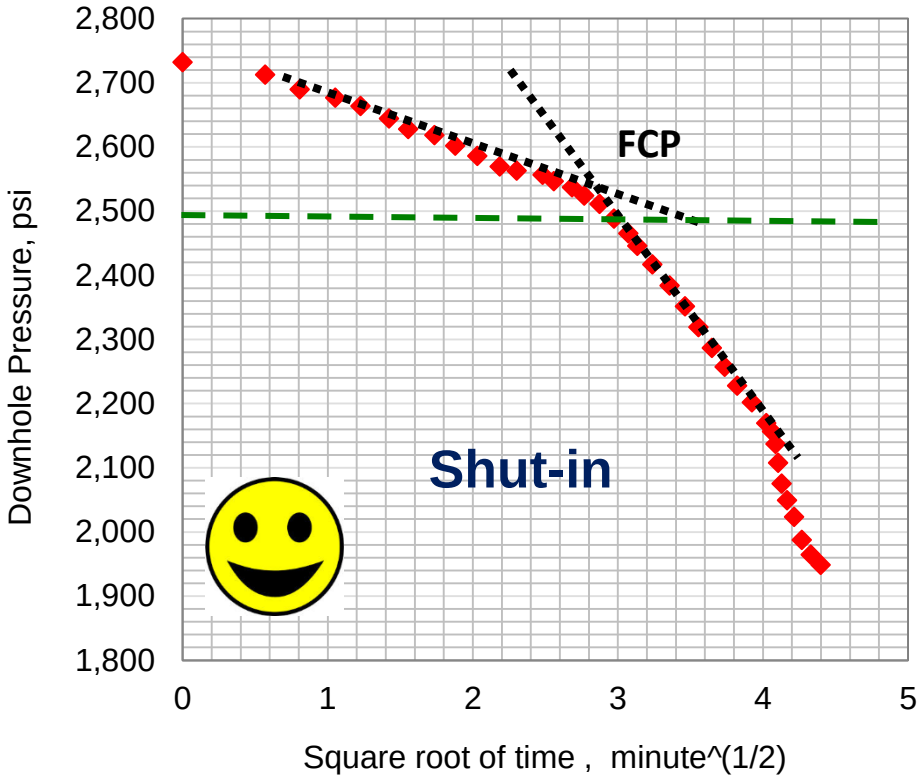
Shut-in

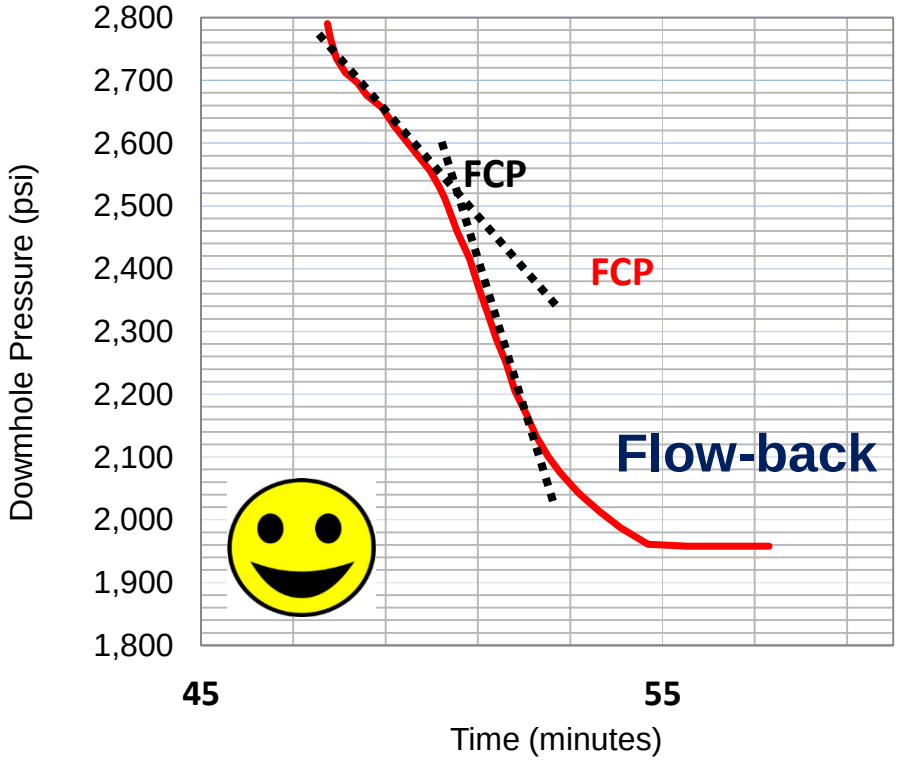


- Low-perm Well 10-7
  - Very small pressure fall-off
  - Fracture remains open, leading to inaccurate prediction of FCP (Shmin).
- High-perm Well 11-2
  - Significant pressure drop
  - Fracture probably got closed, providing a more accurate prediction of FCP

Estimation of Shmin

High Perm: Well 11-2

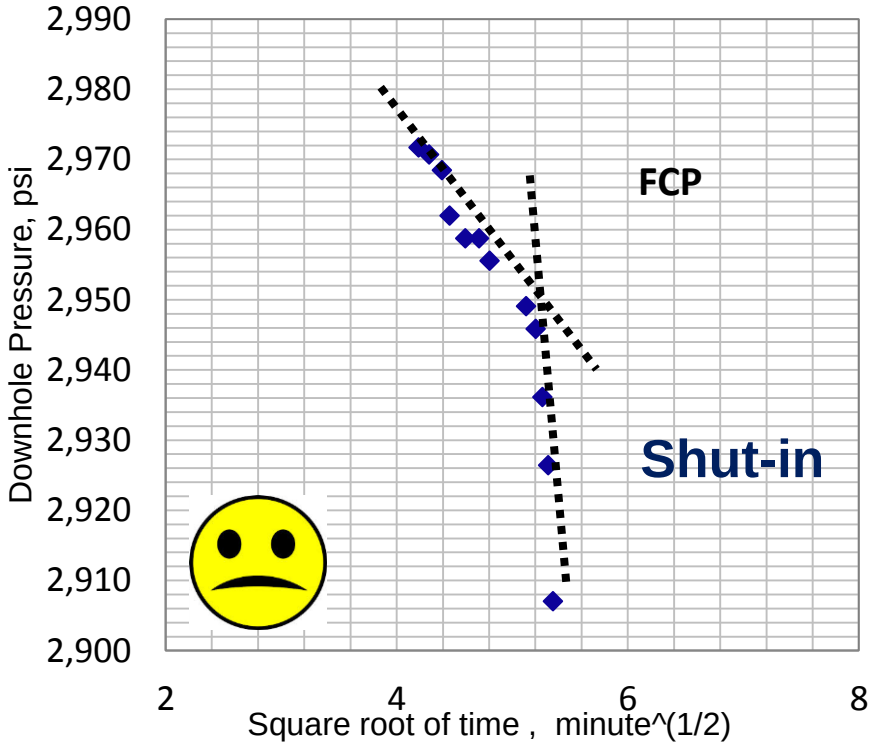


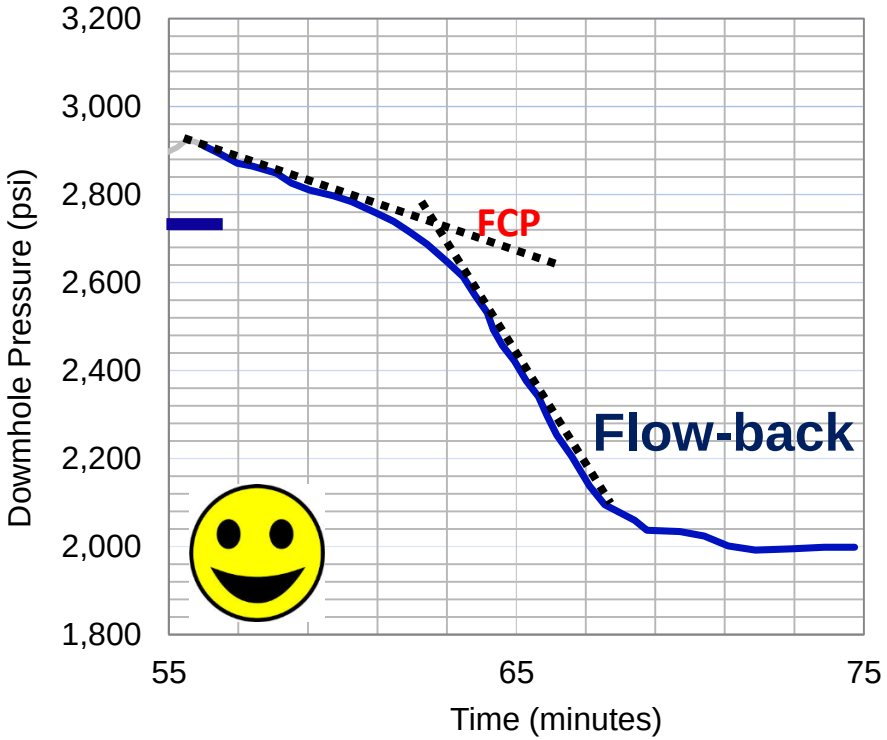


$FCP_{shut\text{-}in}$ (2550psi) ≈ $FCP_{flow\text{-}back}$ (2500psi)

Estimation of Shmin

Low Perm: Well 10-7





$FCP_{shut\text{-}in}$ (2950psi) >>$FCP_{flow\text{-}back}$ (2740psi)

Conclusions

- FIP, LOP, FBP, FPP, and FCP are all affected by rock permeability, fluid leak-off and filter cake development. Ignoring their influences may lead to incorrect interpretation of pump-in/flow-back tests, and consequent drilling problems and unnecessary cost.
- High-perm formations usually has lower FIP compared with low-perm formations. However, a quality filter cake can help maintain or increase LOP and FBP in high-perm formations.
- FIP, LOP and FBP can be very different when “dirty” drilling mud is used as injection fluid, especially in high-perm formations.
- Fluid leak-off leads to high solids-content/viscosity fluid and tight filter cake in the fracture, resulting in an elevated FPP.

Conclusions

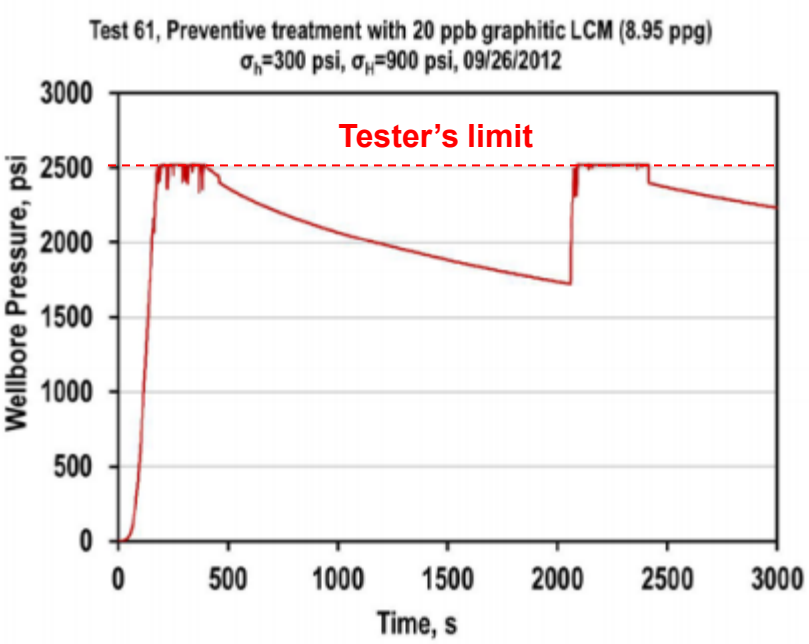
- During shut-in, fracture usually remains open in impermeable formations or permeable formations with tight filter cake in the fracture. Therefore, FCP cannot be properly predicted in these cases.
- A most reliable FCP (Shmin) can be obtained from a flow-back phase, where fracture closure is no longer controlled by permeability or fluid leak-off.
- Identification of formation permeability is critical for pump-in/flow-back test interpretation, especially when drilling mud is used as injection fluid.

Acknowledgments

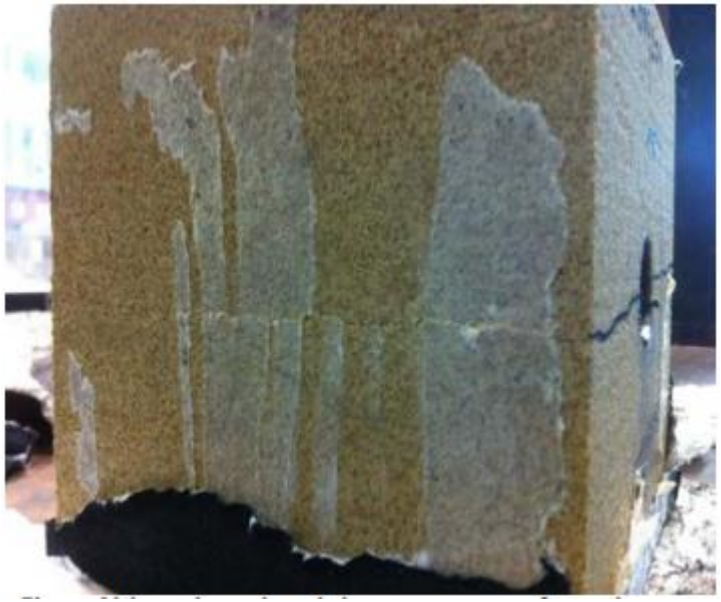
The authors wish to thank the Wider Windows Industrial Affiliate Program, the University of Texas at Austin, for financial and logistical support of this work. Project support and technical discussions with industrial colleagues from the Wider Windows sponsors British Petroleum, Chevron, ConocoPhillips, Marathon, National Oilwell Varco, Occidental Oil and Gas, and Shell are gratefully acknowledged.

Thank you!

Welcome to Questions



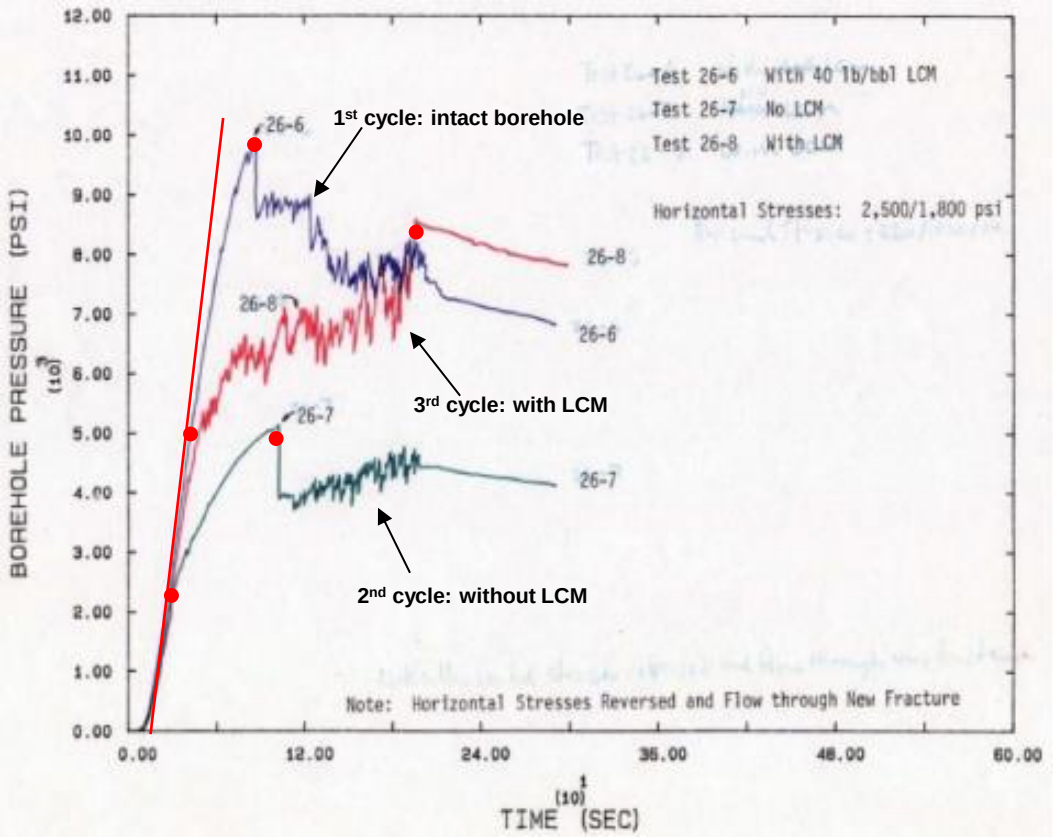
No leak-off from pressure response



Block was fractured to the edge

Guo et al. 2014

- FBP and FPP can be significantly increased by remedial WS treatment, but not LOP



DEA 13 Report, Black 1988